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Direction Finding Performance Analysis for Signal Data Collected during the Storming Bear Exercise

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Defence R&D Canada
DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL MEMORANDUM
DREO TM 2001-031
February 2001

National Defence Défense nationale

Canada

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105-03291/

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TECHNICAL MEMORANDUM
DREO TM 2001-031
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Project
02KS11

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Abstract

This report presents results for the direction finding (DF) experiments carried out using data collected by the Military Digital Analysis System (MiDAS) in November,1999 during the Storming Bear Army exercise. MiDAS is a software radio based communications EW sensor being developed co-operatively by the Communications Research Centre (CRC) and Defence Research Establishment Ottawa (DREO) under the auspices of Defence Research and Development Canada (DRDC) Land Intelligence Electronic Warfare Automation project (LIEWA).

The work described in this report addresses approaches for optimizing the DF processing for signals from tactical frequency hopping radios. The DF approach used in MiDAS is based on the Butler matrix approach in combination with a frequency domain implementation of a digital filter bank receiver. Two closely related practical issues concerning the signal processing approach used to generate DF results were addressed. One issue concerns the optimization of the FFT processing. The data samples from the Butler antenna array can be divided into non-overlapping or overlapping data blocks, resulting in the non-overlapped FFT or the overlapped FFT. The overlapped FFT is theoretically preferable to the non-overlapped FFT, although at a higher computational cost. The other issue concerns the manner in which the angle-of-arrival information from multiple input data blocks is combined or averaged. Both of these issues were investigated by implementing the candidate approaches in Matlab and evaluating their performance using the raw time domain signal data. The results included the identification of a good approach for combining DF results corresponding to multiple blocks of signal data and confirmation that the Butler matrix approach to DF with overlapped FFT processing is distinctly preferable to the same approach with non-overlapped FFT processing.

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Résumé

Le présent rapport montre les résultats d'études radiogoniométriques obtenus à partir des données recueillies par le système d'analyse numérique militaire (MiDAS) en novembre 1999, durant l'exercice Storming Bear de l'Armée de terre. MiDAS est un capteur de GE pour communications radio commandées par logiciel qui est actuellement mis au point conjointement par le centre de recherches sur les communications (CRC) et le centre de recherches pour la défense Ottawa (CRDO) dans le cadre du projet Automatisation du renseignement et de la guerre électronique pour la Force terrestre (ARGEFT) géré par la branche de recherche et développement pour la défense Canada (RDDC). Les travaux décrits dans ce rapport portent sur les méthodes d'optimisation du traitement radiogoniométrique de signaux provenant de postes radios tactiques à sauts de fréquence. La méthode de traitement radiogoniométrique utilisée dans MiDAS combine la méthode à matrice de Butler et une mise en application dans le domaine fréquentiel d'un récepteur à banque de filtres numériques. Deux points pratiques étroitement liés concernant la méthode de traitement des signaux utilisée pour obtenir les résultats radiogoniométriques ont été examinés. L'un de ces points a trait au traitement par transformation de Fourier rapide (TFR) utilisé pour obtenir l'information de phase relative que ser à calculer les valeurs radiogoniométriques. Les échantillons de données du réseau d'antennes de Butler peuvent être divisés en blocs de données sans chevauchement et en blocs avec chevauchement, conduisant à la TFR sans chevauchement et à la TFR avec chevauchement. Théoriquement, la TFR avec chevauchement est préférable à la TFR sans chevauchement, même si les coûts du calcul sont plus élevés. L'autre point a trait à la façon dont on combine les valeurs d'angle d'arrivée fournies par des blocs de données d'entrée multiples sont combinees ou moyenées. Ces points ont été examinés dans le cadre d'une étude consistant à faire le mise en oeuvre et à évaluer les méthodes possibles en se servant de données de signal brutes du domaine temporel. L'étude a permis d'établir une méthode efficace pour combiner les résultats radiogoniométriques correspondant à des blocs multiples de données de signal et de confirmer que la méthode à matrice de Butler pour le traitement radiogoniométrique par TFR avec chevauchement est nettement préférable à la même méthode faisant appel au traitement par TFR sans chevauchement.

Executive summary

This report presents results of an investigation into the design of the algorithms used to implement direction finding (DF) in the Military Digital Analysis System (MiDAS). MiDAS is a software radio based radio surveillance system being developed co-operatively by the Communications Research Centre (CRC) and Defence Research Establishment Ottawa (DREO) under the auspices of Defence Research and Development Canada (DRDC) project LIEWA (Land Intelligence Electronic Warfare Automation). It forms the communications ESM (Electronic Support Measures) sensor component of the LIEWA project. An important concept in MiDAS is that digital filter bank signal processing is used to perform DF on all signals detected within the system instantaneous bandwidth (4.3 MHz for the receivers currently used). Consequently, MiDAS is very much more capable than conventional narrowband communications electronic warfare systems for handling short duration signals, such as frequency hopping and burst signals.

The emphasis on the investigations described in this report concern approaches for optimizing the DF performance achievable for individual hops transmitted by typical tactical frequency hopping radios. The DF approach used in MiDAS is based on a combination of Butler matrix analog time domain processing techniques and a frequency domain implementation of a digital filter bank receiver. Several closely related practical issues affecting the statistical reliability of the DF estimates were addressed.

Two issues concern the Fast Fourier Transform (FFT) processing used to obtain the relative phase information from which the DF results are computed. One issue concerns the design of the FFT filter bank to accommodate signals which will typically be channelized. The other concerns whether the data samples from the Butler antenna array should be arranged in non-overlapping or overlapping data blocks, resulting in the non-overlapped FFT or the overlapped FFT. The overlapped FFT is theoretically preferable to the non-overlapped FFT, although at the cost of additional computation.

A further issue concerns the manner in which the angle-of-arrival information from signal data blocks is combined or averaged. Several reasonable approaches are possible.

These issues were investigated in a study in which significant potential approaches were identified and evaluated using off-the-air time domain signal data. The signal data was collected as part of tests carried out during field trials of MiDAS at the Storming Bear army exercise held in the Eganville-Barry's Bay area during November, 1999. Several frequency hopping radios were operated from known locations and the raw signal data generated by the MiDAS receivers was stored for off-line analysis. As part of the investigation, an effective implementation of the digital filter bank processing was developed and used to evaluate several potential approaches for DF processing using multiple input signal data blocks.

The results obtained provided useful insights into the design of digital filter bank

receivers for processing tactical communications signals. The Butler matrix DF technique was shown to consistently perform better with the overlapped FFT processing than with non-overlapped FFT processing, especially for lower signal-to-noise ratio values. It was also found that that averaging is best done using the complex data preceding the arctangent operation used to obtain angle-of-arrival results (i.e., averaging of the final angle-of-arrival results is suboptimal). Another practical result is the observation that care should be taken to avoid using DF results obtained for blocks of signal data in which the signal starts or ends (and the signal energy in the block is thereby reduced).

François Patenaude, Sichun Wang, Brian Kozminchuk. 2001. Direction Finding Performance Analysis for Signal Data Collected During the Storming Bear Exercise. DREO TM 2001-031. Defence Research Establishment Ottawa.

Sommaire

Le présent rapport presente les résultats d'une étude sur la conception des algorithmes utilisés pour la mise-en-oeuvre traitement radiogoniométrique dans le système d'analyse numérique militaire (MiDAS). MiDAS est un système de surveillance radio commandé par logiciel actuellement mis au point conjointement par le Centre de recherches sur les communications (CRC) et le Centre de recherches pour la défense Ottawa (CRDO) dans le cadre du projet Automatisation du renseignement et de la guerre électronique pour la Force terrestre (ARGEFT) de Recherche et Développement pour la défense Canada (RDDC). Il constitue l'élément capteur de MSE (mesures de soutien électronique) pour les communications du projet ARGEFT. Un concept important de MiDAS est l'utilisation d'une banque de filtres numériques pour le traitement radiogoniométrique de tous les signaux détectés dans la largeur de bande instantanée du système (4,3 MHz pour les récepteurs actuellement utilisés). Par conséquent, MiDAS est beaucoup plus efficace, pour le traitement des signaux à courte durée, comme les signaux à sauts de fréquence et les signaux de salve, que les systèmes de GE communications classiques à bande étroite.

L'accent en ce qui a trait aux études décrites dans ce rapport est mis sur les méthodes d'optimisation du traitement radiogoniométrique réalisable pour des sauts individuels utilisés par des postes radio à sauts de fréquence tactiques. La méthode de traitement radiogoniométrique utilisée dans MiDAS combine des techniques de traitement dans le domaine temporel analogique à matrice de Butler et ain si qu'une mise-en oevvre dans le domaine fréquentiel d'un récepteur à banque de filtres numériques. Plusieurs points pratiques étroitement liés sur concernant la fiabilité statistique des estimations radiogoniométriques ont été examinés.

Deux de ces points ont trait au traitement par transformation de Fourier rapide (TFR) utilisé pour obtenir l'information un la phase relative qui sert à calculer les valeurs radiogoniométriques. L'un a trait à la conception de la banque de filtres à TFR permettant de traiter les signaux qui sont généralement répartis en canaux. L'autre porte sur les travaux visant à déterminer si les échantillons de données provenant du réseau d'antennes de Butler devraient être structurés en blocs de données sans chevauchement ou en blocs avec chevauchement, conduisant à la TFR sans chevauchement et à la TFR avec chevauchement. Théoriquement, la TFR avec chevauchement est préférable à la TFR sans chevauchement, même si les coûts du calcul sont plus élevés.

Un autre point a trait à la façon dont on combine les valeurs d'angle d'arrivée fournies par les blocs de données ou dont on calcule leur moyenne. Plusieurs options raisonnables sont possibles.

Ces points ont été examinés dans le cadre d'une étude qui a permis d'identifier et d'évaluer des méthodes possibles importantes à l'aide de données de signal du domaine temporel captées en direct. Les données ont été recueillies dans des essais sur le terrain de MiDAS effectués au cours de l'exercice Storming Bear de l'Armée de terre, dans la région Eganville-Barry's Bay, en novembre 1999. Plusieurs postes radio à sauts de

fréquence ont été utilisés à partir d'endroits connus et les données brutes du signal générées par les récepteurs MiDAS ont été emmagazinées pour fins d'analyse en différé. Dans le cadre de l'étude, le traitement par banque de filtres numériques a été efficacement mise en oeuvrer et utilisé pour évaluer plusieurs méthodes possibles de traitement radiogoniométrique à l'aide de blocs de données d'entrée multiples.

Les résultats obtenus ont apporté des éclaircissements utiles pour la conception des récepteurs à banque de filtres numériques destinés au traitement des signaux de communications tactiques. On a constaté que la technique de traitement radiogoniométrique à matrice de Butler était toujours plus efficace avec le traitement par TFR avec chevauchement qu'avec le traitement par TFR sans chevauchement, en particulier pour les valeurs inférieures du rapport signal/bruit. On a également constaté que le meilleur calcul de la moyenne s'effectuait avec les données complexes avant l'opération arc-tangente utilisée pour obtenir les valeurs d'angle d'arrivée (c'est-à-dire que le calcul de la moyenne des valeurs finales de l'angle d'arrivée est sous-optimal) On a aussi fait une autre observation pratique: il faut éviter d'utiliser les résultats radiogoniométriques obtenus pour les blocs de données de signal correspondant au début ou à la fin des signaux (l'énergie du signal dans le bloc étant alors réduite).

François Patenaude, Sichun Wang, Brian Kozminchuk. 2001. Direction Finding Performance Analysis for Signal Data Collected During the Storming Bear Exercise. DREO TM 2001-031. Centre de recherches pour la défense, Ottawa.

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1. INTRODUCTION

This report presents the results of an investigation into the algorithm design and optimization for performing Direction Finding (DF) in the MiDAS system. The off-the-air signal data used in the investigation was collected by the MiDAS system in November, 1999 during the Storming Bear army exercise carried out in the Eganville-Barry's Bay area south-west of Petawawa. MiDAS is an acronym for the Military Digital Analysis System, which is being developed cooperatively by the Communications Research Centre (CRC) and Defence Research Establishment Ottawa (DREO) under the auspices of the Defence Research and Development Canada (DRDC) project known as LIEWA (Land Intelligence Electronic Warfare Automation). MiDAS forms the communications ESM (Electronic Support Measures) sensor portion of the LIEWA project.

The emphasis in this report is on investigating ways and means of enhancing the DF performance with particular emphasis on Frequency Hopping signals. The DF approach used in MiDAS is based on the Butler matrix technique. Two closely related practical issues that could have considerable impact on the DF estimates were addressed. One issue concerns the Fast Fourier Transform (FFT) processing used to obtain the relative phase information used to compute the DF results. The data samples from the Butler antenna array can be divided into non-overlapping or overlapping data blocks, resulting in the non-overlapped FFT or the overlapped FFT. The overlapped FFT is theoretically preferable to the non-overlapped FFT, although at a higher computational cost. The other issue concerns the manner in which the angle of arrival information from multiple data blocks is combined or averaged. These two issues were investigated using the raw time domain signal data obtained from a MiDAS system operated near Wilno, Ontario. The results confirmed that the Butler matrix approach to DF consistently provided significantly superior results with overlapped FFTs, especially for lower signal-to-noise ratios (SNRs), if the DF information from the data blocks is appropriately combined.

The report is organized as follows. In Section 2, three different versions of the Butler matrix approach to direction finding are introduced, where either overlapped or non-overlapped FFTs are employed. In Section 3, the results for direction finding are presented and discussed. Finally, Section 4 provides some concluding remarks.

2. THE BUTLER MATRIX APPROACH TO DIRECTION FINDING

This section presents three different versions of the Butler matrix approach to direction finding and discusses the five different ways of data segmentation that were used prior to estimation of the angle-of-arrival.

2.1 Three Versions of the Butler Matrix Approach to Direction Finding

In the Butler matrix approach to direction finding, a circular array of equally spaced antennae is used. The received signals from the antenna elements are appropriately combined, sampled and quantized, yielding two data output streams. These two data streams are termed the reference signal and the mode one signal and denoted by r_k and s_k respectively. The data streams r_k and s_k are separated into blocks of equal length (overlapping or non-overlapping), read into the computer memory block by block, windowed by a windowing sequence such as the Blackman window, and then transformed into the frequency domain using the FFT. For each block of input data, an angle of arrival can be derived from the phase information obtained from the phase data computed from the resulting FFT data. From theoretical arguments, the use of windowed FFTs on non-overlapping blocks or segments of signal data is suboptimal in that the window function reduces the effective duration or length of each block of data. Consequently, it is expected that if the data sequences r_k and s_k are divided into overlapping instead of non-overlapping blocks and if the DF information from the overlapping blocks is appropriately averaged or combined, better DF performance should be achieved. This is especially an issue for short duration signals, such as those transmitted by frequency hopping radios, where the amount of signal data available for processing is limited. In preliminary analyses, five different approaches to combining DF information from consecutive input data blocks were considered. Three of these five approaches exhibited noticeably better performance than the other two. More complete analyses were then conducted using these three approaches.

The three implementations of the Butler matrix approach to direction finding will now be presented.

Let $L > 0$ be the length of the FFT to be applied and $J \geq 1$ the number of overlapping data blocks of length L used in the angle of arrival estimation. Let γ be a non-negative rational number such that γL is an integer. Let the windowing sequence be defined by $\mathbf{h} = (h_0, h_1, \cdots, h_{L-1})^t$, where $\mathbf{h}$ is a linear phase FIR filter of length L. Divide the signal sequences r_k and s_k into sample vectors $\mathbf{R}_j, \mathbf{S}_j$, each of length L,

$-\infty < j < \infty$, as follows :

$$(1)\begin{cases} \mathbf{R}_0 = (r_0, & r_1, & \cdots, & r_{L-1})^t \\ \mathbf{R}_1 = (r_{(1-\gamma)L}, & r_{(1-\gamma)L+1}, & \cdots, & r_{(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \\ \mathbf{R}_k = (r_{k(1-\gamma)L}, & r_{k(1-\gamma)L+1}, & \cdots, & r_{k(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \\ \mathbf{R}_{J-1} = (r_{(J-1)(1-\gamma)L}, & r_{(J-1)(1-\gamma)L+1}, & \cdots, & r_{(J-1)(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \end{cases}$$

$$(2)\begin{cases} \mathbf{S}_0 = (s_0, & s_1, & \cdots, & s_{L-1})^t \\ \mathbf{S}_1 = (s_{(1-\gamma)L}, & s_{(1-\gamma)L+1}, & \cdots, & s_{(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \\ \mathbf{S}_k = (s_{k(1-\gamma)L}, & s_{k(1-\gamma)L+1}, & \cdots, & s_{k(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \\ \mathbf{S}_{J-1} = (s_{(J-1)(1-\gamma)L}, & s_{(J-1)(1-\gamma)L+1}, & \cdots, & s_{(J-1)(1-\gamma)L+L-1})^t \\ \cdots \quad \cdots & \cdots & \cdots & \cdots \end{cases}$$

where each vector has γL samples in common with the preceding vector. The vectors $\mathbf{R}_j, \mathbf{S}_j$ are windowed by the windowing sequence h and transformed by the discrete Fourier transform matrix $\mathbf{F}$ of dimensions $L \times L$, resulting in the FFT vectors $\mathbf{X}_j = \mathbf{FWR}_j$, $\mathbf{Y}_j = \mathbf{FWS}_j$, $-\infty < j < \infty$, where $\mathbf{W}$ is the diagonal matrix of dimensions $L \times L$, i.e.,

$$(3) \qquad \mathbf{W} = \begin{pmatrix} h_0 & 0 & 0 & 0 & \cdots \\ 0 & h_1 & 0 & 0 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & h_{L-1} \end{pmatrix}$$

The complex vector $\mathbf{A}_j = (a_{0,j}, a_{1,j}, \cdots, a_{L-1,j})$ is defined as the component-wise product of the vectors $\mathbf{Y}_j$ and $\mathbf{X}_j^*$, where $\mathbf{X}_j^*$ is the complex conjugate of $\mathbf{X}_j$. Specifically,

$$(4) \qquad a_{k,j} = (y_{k,j})(x_{k,j})^*, \quad 0 \le k \le L-1, \quad -\infty < j < \infty,$$

where $y_{k,j}$ and $x_{k,j}$ are the $(k+1)$-th components of the vectors $\mathbf{Y}_j$ and $\mathbf{X}_j$ respectively, and $(y_{k,j})^*$ is the complex conjugate of $y_{k,j}$. Assume each channel occupies K bins and out of the K bins in a channel, only the N center bins are used in the computation of the angle-of-arrival. For the signal in the channel specified by the K bins $m, m+1, m+K-1$, where $m \ge 0$ is some integer, its angle-of-arrival corresponding to the j-th input data block and denoted by θ_j, can be estimated using the J vectors $\mathbf{A}_j, \mathbf{A}_{j-1}, \cdots, \mathbf{A}_{j-J+1}$. Three methods have been proposed here.

2.1.1 Butler Method 1

The mean value of the complex vectors $\mathbf{A}_j, \mathbf{A}_{j-1}, \cdots, \mathbf{A}_{j-J+1}$, denoted by $\mathbf{C}_j$, is computed according to

$$\mathbf{C}_j = \frac{\mathbf{A}_j + \mathbf{A}_{j-1} + \cdots + \mathbf{A}_{j-J+1}}{J}$$

$$= (c_0, c_1, \cdots, c_{L-1}). \tag{5}$$

The bearing θ_j is then defined by

$$\theta_j = \arctan 2 \left(\text{real} \left(\sum_{k=0}^{N-1} c_{m+(K-N)/2+k} \right), \text{imag} \left(\sum_{k=0}^{N-1} c_{m+(K-N)/2+k} \right) \right) \tag{6}$$

2.1.2 Butler Method 2

The complex vectors $\mathbf{A}_j$ are modified according to the following equation, resulting in a new complex vector sequence $\mathbf{B}_j$, i.e.,

$$\mathbf{B}_j = \left(\left(\sqrt{|a_{0,j}|} \right) a_{0,j}, \left(\sqrt{|a_{1,j}|} \right) a_{1,j}, \cdots, \left(\sqrt{|a_{L-1,j}|} \right) a_{L-1,j} \right) \tag{7}$$

The idea of this modification is to place more emphasis on the stronger FFT samples. The mean value of the modified complex vectors $\mathbf{B}_j, \mathbf{B}_{j-1}, \cdots, \mathbf{B}_{j-J+1}$ to obtain a weighted average $\mathbf{D}_j$ are computed according to

$$\begin{aligned} \mathbf{D}_j &= \frac{\mathbf{B}_j + \mathbf{B}_{j-1} + \cdots + \mathbf{B}_{j-J+1}}{J} \\ &= (d_0, d_1, \cdots, d_{L-1}) \end{aligned} \tag{8}$$

The bearing θ_j is then defined by

$$\theta_j = \arctan 2 \left(\text{real} \left(\sum_{k=0}^{N-1} d_{m+(K-N)/2+k} \right), \text{imag} \left(\sum_{k=0}^{N-1} d_{m+(K-N)/2+k} \right) \right) \tag{9}$$

2.1.3 Butler Method 3

Each of the complex vectors $\mathbf{A}_j$ gives rise to an angle-of-arrival β_j for the channel specified by the bins $m, m+1, \cdots, m+K-1$ according to

$$\beta_j = \arctan 2 \left(\text{real} \left(\sum_{k=0}^{N-1} a_{m+(K-N)/2+k,j} \right), \text{imag} \left(\sum_{k=0}^{N-1} a_{m+(K-N)/2+k,j} \right) \right) \tag{10}$$

The bearing θ_j is then defined as the mean value of the angles $\beta_j, \beta_{j-1}, \cdots, \beta_{j-J+1}$

$$\theta_j = \frac{\beta_j + \beta_{j-1} + \cdots + \beta_{j-J+1}}{J} \tag{11}$$

The above three methods all seem to be reasonable approaches for smoothing out fluctuations in the DF estimates. However, it turns out that Butler Method 1 has the best performance.

2.2 Five Different Ways of Data Segmentation

In the definitions in Subsection 2.1, $\gamma = 0$ actually corresponds to non-overlapping data segments, while $\gamma > 0$ corresponds to the overlapping case. Among all overlapping ratios $\gamma > 0$, $\gamma = 0.5$ is believed to be a good choice, since experience with analogous approaches to spectral analysis (e.g., the Welch power spectral density estimator) suggests that any performance gain obtained by increasing the value beyond 0.5 will be negligible relative to the increase in computational cost. In this study, we only investigate the two cases $\gamma = 0$ (non-overlapping) and $\gamma = 1/2$ (overlapping). To make meaningful comparisons between the non-overlapping FFT approach and the overlapping FFT approach, it is essential that the comparisons be based on the same amount of input data (i.e., the signal duration is fixed). Since the analysis of the data is very complex, we have chosen to concentrate on the following five scenarios, which may also be of most practical interest:

1. $J = 1$ and $\gamma = 0$. In this case, DF information is obtained from each single input data block. No DF information is required from earlier blocks of input data. This case requires two FFTs and will be referred to as the non-overlapping case N1. The performance of the Butler matrix approach to direction finding for the non-overlapping case N1 is studied and documented in [4], where extensive simulation results regarding FFT CFAR detectors can be found.

2. $J = 2$ and $\gamma = 0$. In this case, in addition to DF information from the current input data block, the DF information from the preceding non-overlapping input data block is also taken into account. There are altogether two consecutive non-overlapping input blocks used in the estimation. This case will be referred to as the non-overlapping case N2. The computational cost for this case is the same as that for the case N1.

3. $J = 3$ and $\gamma = 0$. In this case, in addition to DF information from the current input data block, the DF information from the two preceding non-overlapping input data blocks is also taken into account. There are altogether three consecutive non-overlapping input blocks used in the angle-of-arrival estimation. This case will be referred to as the non-overlapping case N3. The computational cost is the same as that for the case N1. The non-overlapping cases N4, N5, etc., are similarly defined.

4. $J = 3$ and $\gamma = 0.5$. In this case, there are two non-overlapping input data blocks, the current input block and the preceding input block. These two non-overlapping blocks are segmented into three overlapping blocks The angle-of-arrival estimate is computed using information from the three overlapping blocks. There are four FFT computations and hence the computational cost doubles that of the non-overlapping case N1. This case will be referred to as the overlapping case O3.

5. $J = 5$ and $\gamma = 0.5$. In this case, there are three non-overlapping input data blocks, the current input block and the two preceding input blocks. These three non-overlapping data blocks are segmented into five overlapping data blocks. The

angle-of-arrival estimate is computed using information from the five overlapping blocks. There are four FFT computations and hence the computational cost doubles that of the non-overlapping case N1. This case will be referred to as the overlapping case O5. The overlapping cases O2, O4, O6, O7, etc., are similarly defined.

It should be emphasized that the non-overlapping case N2 requires the same amount of input data as the overlapping case O3 and similarly the non-overlapping case N3 requires the same amount of input data as the overlapping case O5. Since the smallest amount of input data is used in the non-overlapping case N1, it may be expected that the cases N2, N3, O3 and O5 all should outperform the case N1. This was indeed confirmed in the study. Also, it was found that the overlapping cases O3 and O5 outperformed the non-overlapping cases N2 and N3 respectively. Hence by using DF information from a few consecutive overlapping data blocks instead of non-overlapping data blocks, the standard deviation of the angle-of-arrival is reduced. Detailed discussions of the results will be given in the following section.

3. PERFORMANCE COMPARISONS

This section provides an overview of the data files that were used in the studies, discusses the issues of adding artificial Gaussian noise to the samples from the data on the CDs, presents the computation methods for calculating the standard deviation of the angle-of-arrival for the frequency hopping signals and, finally, the bearing estimation results.

3.1 An Overview of the Data Files in the Simulations

The raw data used in the studies were collected and stored on several CDs during the Storming Bear field trials. Most of the data files were based on a MiDAS sampling rate of 5.12 MHz. The receivers were set to a frequency of 45 MHz, and the complex baseband bandwidth was 4.5 MHz. In all tests, DREO's Jaguar V's were used as the signal sources. These radios were placed at various positions some distance from the MiDAS collection equipment. Some captures which were questionable in nature were made, probably caused by coordination problems between the data collectors and the radio operators. The details associated with the collections are listed in Tables 3.1, 3.1, 3.1 and 3.1.

Each of the CDs contains from 4 to 8 data files, totaling 64 Mbytes of data samples. Some of the data was of questionable quality as mentioned above, particularly on disks 1 to 4. The data files on disks 5-8 were of high quality. To illustrate the good quality of the data samples in disks 5-8 and the poor quality of data samples in disks 1-4, two representative spectrograms are plotted here. The spectrogram in Fig. 1(a) was obtained by using data samples from the first file on disk 7 and the spectrogram in Figure 1(b) was obtained by using data samples from the fifth file from disk 3. Figure 1(a) clearly shows the existence in the data of at least two frequency hopping signals of different power levels as well as a fixed frequency signal. In sharp contrast to Fig. 1(a), Fig. 1(b) does not show clearly at all the presence of any signal in the data. Due to time constraints, only three files were selected and tested in our studies, one from each of the disks 5-7. The signal-to-noise ratio for the data in disks 5-7 was high, sometimes as high as 45 dB. To evaluate the Butler matrix approach to direction finding for low SNR scenarios, artificially generated Gaussian noise samples were added to the signal samples read from these CDs.

3.2 The Addition of Artificial Gaussian Noise to the Signals

Assume the FFT length is L and there are K bins and N used bins in each channel. The signal-to-noise ratio for a signal is defined in the frequency domain on the dB scale by

$$SNR = 10\log 10\left(\frac{P_s}{NP_n}\right) \tag{12}$$

where P_s is the signal power in the N used center bins and P_n is the noise power per bin. In the time domain, let the original data samples read from a disk be denoted by

Table 1: Collection Parameters for Disk 3, File 5

File Name	Wilno32-35-19991117-110152.das
File Description	Wilno-lookout
Date/Time	11/17/99 11:01 AM
Number of Points	16777216
Rx Center Frequency (Hz)	45000000
Rx Gain (dB)	0
A/D Scale Factor (Volt)	2.81637E-06
A/D Range (dBm)	-18
MiDAS Center Frequency (Hz)	5120000
Signal Bandwidth (Hz)	4505600
Sampling Rate (Hz)	5120000
Array Resolution (Byte)	2
Number of A/Ds	2

Table 2: Collection Parameters for Disk 5, File 1

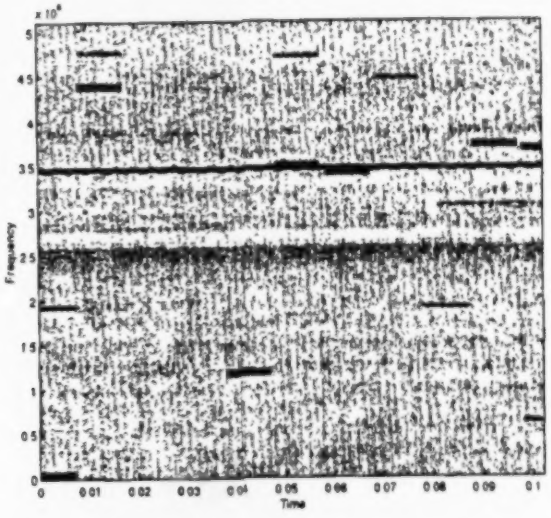
File Name	2jagvs-19991117-154457.das
File Description	
Date/Time	11/17/99 3:44 PM
Number of Points	16777216
Rx Center Frequency (Hz)	45000000
Rx Gain (dB)	0
AD Scale Factor (Volt)	2.81637E-06
A/D Range (dBm)	-18
MiDAS Center Frequency (Hz)	5120000
Signal Bandwidth (Hz)	4505600
Sampling Rate (Hz)	5120000
Array Resolution (Bytes)	2
Number of A/Ds	2

Table 3: Collection Parameters for Disk 6, File 1

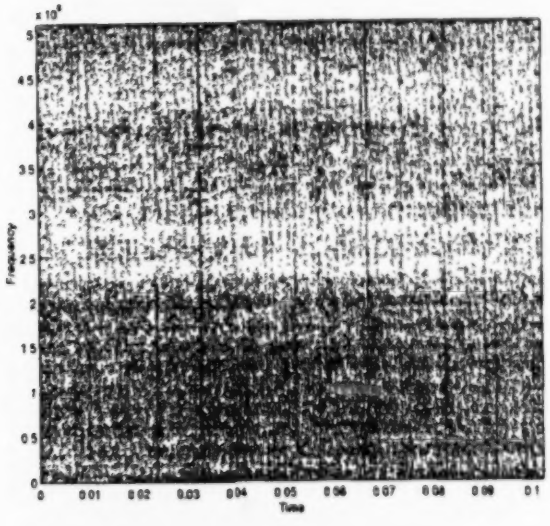
File Name	2jagvs-19991117-161207.das
File Description	
Date/Time	11/17/99 4:12 PM
Number of Points	16777216
Rx Center Frequency (Hz)	45000000
Rx Gain (dB)	0
A/D Scale Factor (Volt)	2.81637E-06
A/D Range (dBm)	-18
MiDAS Center Frequency (Hz)	5120000
Signal Bandwidth (Hz)	4505600
Sampling Rate (Hz)	5120000
Array Resolution (Byte)	2
Number of A/Ds	2

Table 4: Collection Parameters for Disk 7, File 1

File Name	2jagvclose-19991117-170229.das
File Description	2 jagvs 100 meters apart unsync
Date/Time	11/17/99 5:02 PM
Number of Points	16777216
Rx Center Frequency (Hz)	45000000
Rx Gain (dB)	0
A/D Scale Factor (Volt)	2.81637E-06
A/D Range (dBm)	-18
DAS Center Frequency (Hz)	5120000
Signal Bandwidth (Hz)	4505600
Sampling Rate (Hz)	5120000
Array Resolution (Byte)	2
Number of A/Ds	2



(a)



(b)

Figure 1: *(a) Spectrogram obtained from data in file 1 of disk 7; (b): Spectrogram obtained from data in file 5 of disk 3.*

y_k, $k = 0, 1, 2, \cdots,$. The received signal samples y_k can be divided into a signal component x_k and a noise component n_k as in

$$y_k = x_k + n_k \tag{13}$$

Let $\sigma \geq 0$ be a non-negative scaling constant. If an independent identically distributed Gaussian random sequence n'_k is added to the received signal sample sequence y_k, where n'_k is independent of the original noise sample sequence n_k and has a standard deviation equal to σ times that of n_k, a new signal sequence y'_k results, i.e.,

$$y'_k = x_k + n_k + n'_k \tag{14}$$

The signal-to-noise ratio for this new signal y'_k can now be computed. In fact, let the signal-to-noise ratio for y'_k be denoted by SNR'. Then,

$$SNR' = 10\log10\left(\frac{P_s}{NP_n + NP'_n}\right) \tag{15}$$

where P'_n is the noise power per bin for the noise samples n'_k. Since the standard deviation of the added noise sample sequence n'_k is σ times that of the original noise sample sequence n_k, it follows that in the frequency domain

$$P'_n = \sigma^2 L P_n \tag{16}$$

where L is the length of the FFT. Substituting Eq. 16 into Eq. 15,

$$\begin{aligned} SNR' &= 10\log10\left(\frac{P_s}{NP_n + N\sigma^2 L P_n}\right) \\ &= 10\log10\left(\frac{P_s}{NP_n(1+\sigma^2 L)}\right) \\ &= 10\log10\left(\frac{P_s}{NP_n}\right) + 10\log10\left(\frac{1}{1+\sigma^2 L}\right) \\ &= SNR - 10\log10\left(1+\sigma^2 L\right) \end{aligned} \tag{17}$$

Therefore,

$$SNR - SNR' = 10\log10\left(1+\sigma^2 L\right) \tag{18}$$

The quantity $SNR - SNR'$ on the left side of the preceding equation is nothing but the difference in dB between the signal-to-noise ratio of the original signal y_k and that of the new signal y'_k. The scaling factor σ is easily solved from Eq. 18, i.e.,

$$\sigma = \sqrt{\frac{10^{\frac{SNR-SNR'}{10}} - 1}{L}} \tag{19}$$

To simulate the noise effect on the DF performance in the studies carried out, the variance of the noise component n_k in the signal samples r_k(see Eq. 13) was first

estimated, using 200 consecutive data blocks each of length 1024. The signal-to-noise ratios for the detected signals were then estimated by estimating the power levels of the detected signals. The difference in signal-to-noise ratio $SNR - SNR'$ was increased in increments of 5 dB, the corresponding σ was computed according to Eq. 19 and then an appropriately generated Gaussian noise sample sequence n'_k was added to the sample sequence y_k. Finally the angles-of-arrival for the detected signals were computed.

3.3 Computation of Bearing Standard Deviation for FH Signals

To make a fair comparison among the different implementations of the Butler matrix approach to direction finding, the standard deviation of the angle-of-arrival results obtained for the same blocks of signal data should be computed. This is achieved by using a single common detector to determine the signal data to be processed. After a signal is detected, its angle-of-arrival is computed using the three implementations, namely, Butler Method 1, Butler Method 2 and Butler Method 3, for the five different cases N1, N2, N3, O3, O5. The sampling rates for the three tested files in the simulations are all the same and equal to 5.12 MHz. The frequency hopping signals in the disk files are known to have a bandwidth of 25 KHz. The FFT length was 1024, yielding a bin width of 5 kHz and $K = 5$ bins for each channel and, consequently $N = 3$ center bins in each channel were used for detection and direction finding. Moreover, an 80 per cent spectral efficiency was assumed which implies that some channels on the edges of the sampled bandwidth were removed in order to avoid using corrupted FFT samples. In the studies, 10,000 data blocks, each of length 1024, were read in from a data file into the computer memory on a block by block basis. These data blocks were processed as explained earlier. If a signal (or signals) was (were) detected, the data block index, the detected channel frequencies and the angles of arrival were all stored in a large array in the Matlab environment. Individual hops of the frequency hopping signals were then isolated by searching for channels containing significant spectral energy. The fixed frequency signals, if any, were also identified and the corresponding spectral data ignored. We singled out two frequency hopping signals from the first file in disk 5, two frequency hopping signals from the first file of disk 6 and one fixed frequency signal from the first file of disk 6. The first file in Disk 7 was also studied but the results were not analyzed systematically due to time constraints. All of the frequency hopping signals considered have the same hop duration of $45 * 1024/(5.12 * 10^6) = 0.009$ seconds or 9 milliseconds. In our computations of the standard deviation of angle-of-arrival, 19 hops were used for all the frequency hopping signals. In each hop there were 45 angle-of-arrival estimates. Hence altogether there are $19 * 45 = 855$ estimates for the angle-of-arrival for each frequency hopping signal. The standard deviation is computed based on these 855 angle-of-arrival estimates. To make the comparisons consistent, the standard deviation of the angle-of-arrival for the fixed frequency signal from the first file of disk 6 was also computed using 855 estimates. The results of the study will now be presented.

3.4 Bearing Estimation Results

For the first file of disk 5, one of the two identified frequency hopping signals was from a direction of 1.6158 radians or 93 degrees with an SNR of about 45 dB. The other signal was from a direction of 1.5145 radians or 87 degrees with an SNR also at about 45 dB. These two signals will be called, respectively, signal number one and signal number two.

For the first file of disk 6, one of the two identified frequency hopping signals was from a direction of 2 radians or 115 degrees with an SNR of about 43 dB. This signal is called signal number one. The other frequency hopping signal was from a direction of 1.92 radians or 110 degrees with an SNR of about 40 dB. This signal is called signal number two. The fixed frequency signal from the first file of disk 6 was from a direction of 1.785 radians or 102 degrees with an SNR of about 30 dB. This signal is called signal number three.

It is first shown that, among the three versions of the Butler matrix approach to direction finding, Butler Method 1 exhibits the best performance. In Figs. 2-4, for the two frequency hopping signals in disk 5, file 1, the standard deviation of the angle-of-arrival is plotted as a function of SNR, where the three Butler methods are compared for different overlapping or non-overlapping scenarios. It is evident from these plots that Butler Method 1 performs better than the other two Butler methods. This pattern persists for the two frequency hopping signals and the one fixed frequency signal in disk 6, file 1. Since the standard deviation exhibits very similar behavior for the signals in disk 6, file 1, the plots are omitted.

Recall that in the overlapping case N3 and the non-overlapping case O5, the same amount of data are involved in the estimation of angle-of-arrival (three non-overlapping data blocks for N3 or five overlapping blocks for O5). It is interesting to observe that for these two cases N3 and O5, Butler Method 3 has significantly larger standard deviation compared to the other two Butler Methods, even for high SNR values. This seemingly strange behaviour of Butler Method 3 actually reveals an important aspect of the Butler matrix approach to DF. At the beginning and at the end of each hop, Butler Method 3 may involve averaging unreliable angle-of-arrival estimates, since three non-overlapping data blocks or five overlapping data blocks are used in computing the angle-of-arrival. Among these data blocks, one or even two may have low signal levels (due to the non-zero rise and fall times at the hop edges). If a few angle-of-arrival estimates are discarded at the beginning and at the end of each hop, one should expect that Butler method 3 would have similar performance to the other two methods. In fact, if two angle-of-arrival estimates are removed from the beginning and two more angle-of-arrival estimates are removed from the end of each hop, and the standard deviation is recomputed using the remaining angle-of-arrival estimates in the middle of the hops, Butler Method 3 has almost identical performance to Method 1 and Method 2. The recomputed standard deviation is plotted in Fig. 5 for signal number one from disk 5, file 1 for the cases N3 and O5. The implication of the above discussion is that one should try to avoid using DF estimates corresponding to the edges of the hop envelopes

because these estimates may be poor in quality and substantially degrade DF performance.

It is shown next that for Butler Method 1, increasing the number of consecutive input data blocks, whether or not they are overlapped or non-overlapped, will steadily improve the DF performance. In Fig. 6, the standard deviation of angle-of-arrival is plotted as a function of SNR, where the three non-overlapping approaches N1, N2 and N3 are compared in Fig. 6(a) and the four overlapping approaches O2, O3, O4 and O5 are compared in Fig. 6(b). It is evident that the DF performance improves as the number of data segments (overlapped or non-overlapped) used for direction finding increases. However, the improvement diminishes as the number of data segments becomes larger. Also, systematic errors, such as in the phase matching of the receivers, will limit the practical improvement. Consequently, reasonable choices for the number of segments are 5 for overlapping data segments and 3 for non-overlapping data segments. The results for the two frequency hopping signals and the one fixed frequency signal in disk 6, file 1 are very similar and hence have been omitted here.

Finally, we show that for Butler method 1, the overlapped FFT approach outperforms the non-overlapped FFT approach. In Fig. 7, the standard deviation of angle-of-arrival is plotted as a function of SNR, where in Fig. 7(a), the three non-overlapping approaches N1, N2 and N3 are compared with the two overlapping approaches O3 and O5 for signal one in disk 5, file 1, while in Fig. 7(b), the three non-overlapping approaches N1, N2 and N3 are compared with the two overlapping approaches O3 and O5 for signal two in disk 5, file 1. Recall that the non-overlapping approach N2 uses the same amount of input data as the overlapping approach O3 and the non-overlapping approach N3 uses the same amount of input data as the overlapping approach O5. It is evident from these plots that O3 and O5 outperform N2 and N3 respectively. Again, the results for the two frequency hopping signals and the one fixed frequency signal in disk 6, file 1 are very similar and have been omitted.

From Fig. 7, it can be observed that at $SNR = 5$ dB, O3 outperforms N2 by almost 10 degrees and O5 outperforms N3 by about 7 degrees. At 10 dB, N2 outperforms N1 by about 6 degrees, O3 outperforms N2 by about 3 degrees and O5 outperforms N3 by about 2 degrees.

To visually demonstrate the angle-of-arrival results, in Fig. 8 to 9, the angle-of-arrival estimates corresponding to the 19 isolated hops are plotted. Here, the radius represents the channel frequencies of the hops and the angle represents the angle-of-arrival.

4. CONCLUSIONS AND RECOMMENDATIONS

The studies reported here confirm the idea that using overlapping blocks of signal data with an overlapping ratio of 0.5 provides practical benefits in the DF performance with the FFT implementation of the Butler matrix direction finding approach. The DF information from the overlapping input data blocks should be combined as described by Butler method 1 (for example, see Eq. 6). Reasonable choices for the number of overlapping blocks would be either 3 or 5. Another consideration is that care should be used to ensure that significant signal energy is not lost by using data records including signal data corresponding to the edges of the hop envelope.

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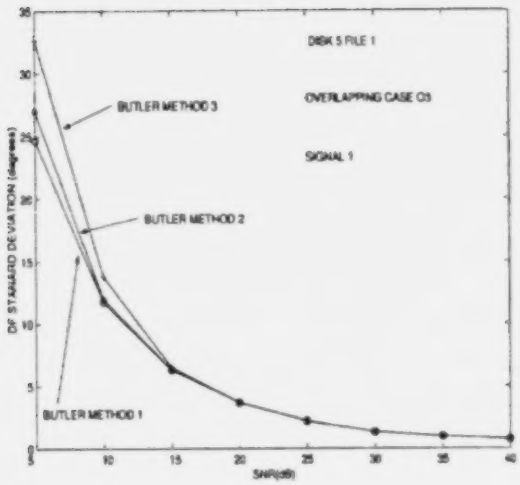

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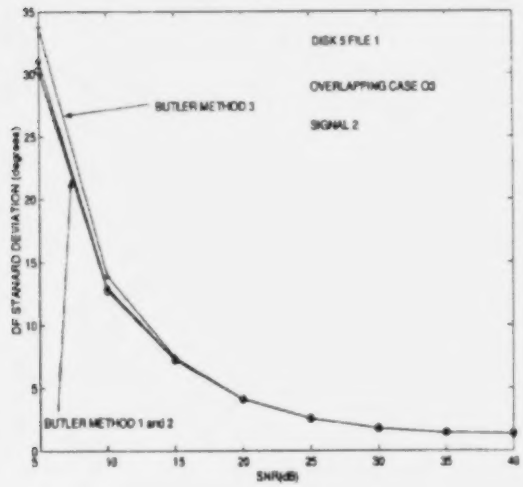
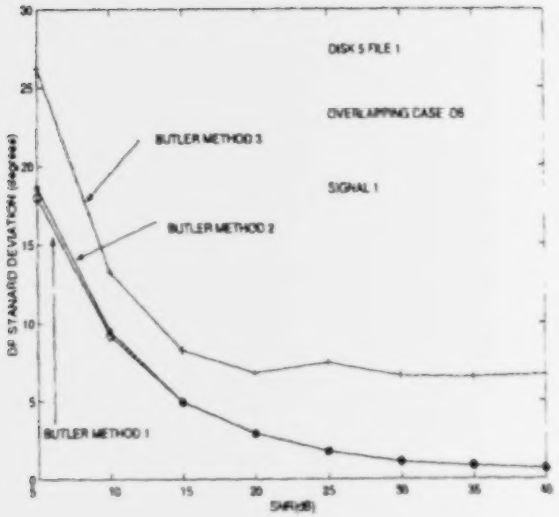


(b)

Figure 2: *Comparing the standard deviation for the three Butler methods using the two frequency hopping signals in disk 5, file 1 (overlapping case O3). (a) Signal 1 in Disk 5, (b) Signal 2 in Disk 5*



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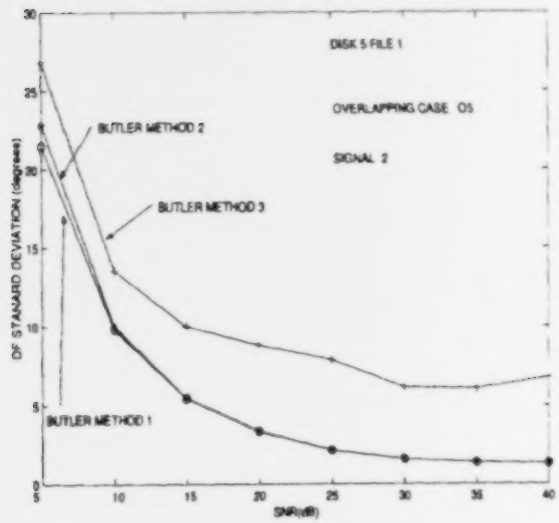

(b)

Figure 3: *Comparing the standard deviation for the three Butler methods using the two frequency hopping signals in disk 5, file 1 (overlapping case O5): (a) Signal 1 in Disk 5; (b) Signal 2 in Disk 5*

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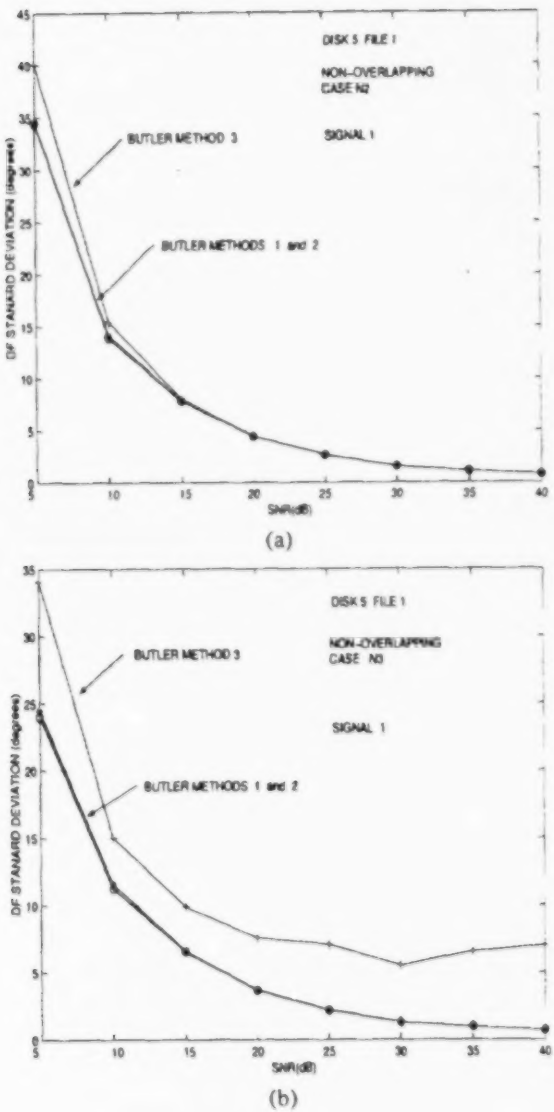

Figure 4: *Comparing the standard deviation for the three Butler methods using the frequency hopping signal 1 in disk 5, file 1: (a) Non-overlapping case N2, (b) Non-Overlapping case N3.*

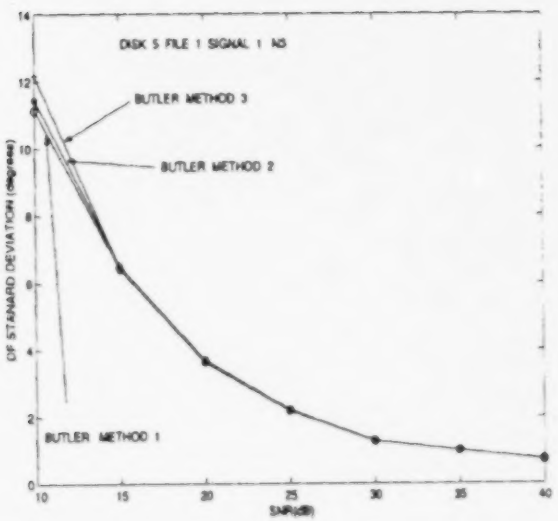

Figure 5: *Comparing the standard deviation for the three Butler methods using the frequency hopping signal 1 in disk 5, file 1 (after removing two angle-of-arrival estimates from the beginning and two angle-of-arrival estimates from the end of each hop): (a) Non-Overlapping Case N3; (b) Overlapping Case O5.*

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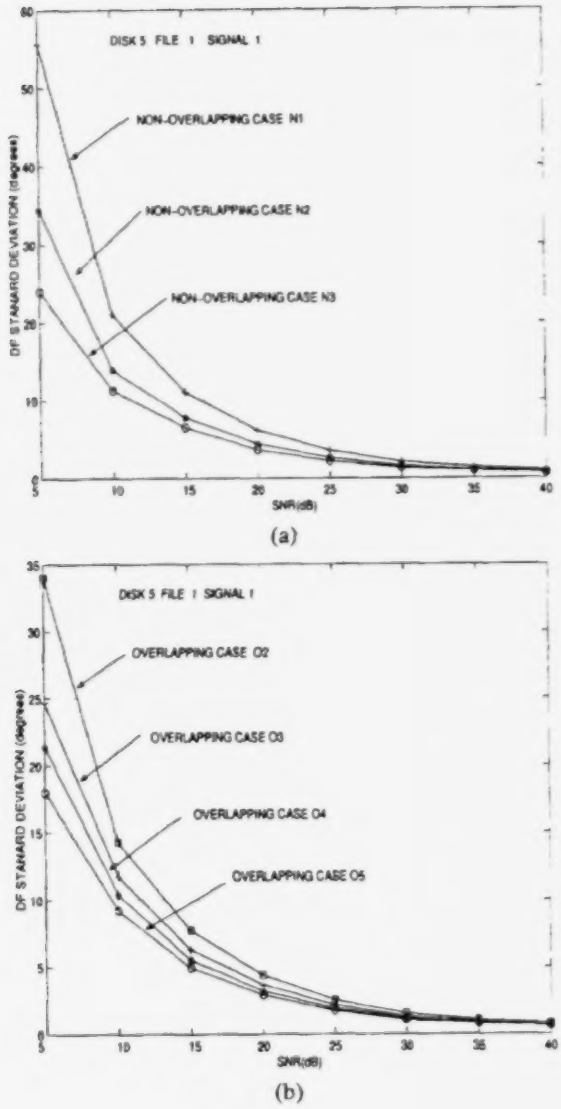

Figure 6: *Comparing the standard deviation computed via Butler method 1 using the frequency hopping signal 1 in disk 5, file 1. (a) The three non-overlapping cases N1, N2, N3, (b) The four overlapping approaches O2, O3, O4, O5.*

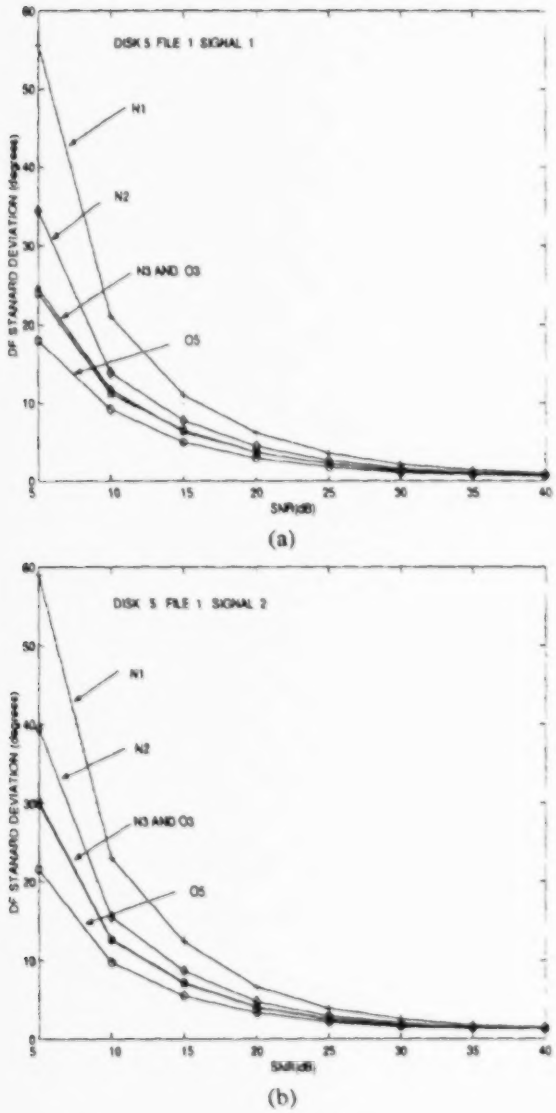

Figure 7: *Comparing the standard deviation computed via Butler method 1 for the three non-overlapping cases N1, N2, N3, and the two overlapping cases O3, O5. (a) Signal 1 in disk 5, file 1; (b) Signal 2 in disk 5, file 1;*

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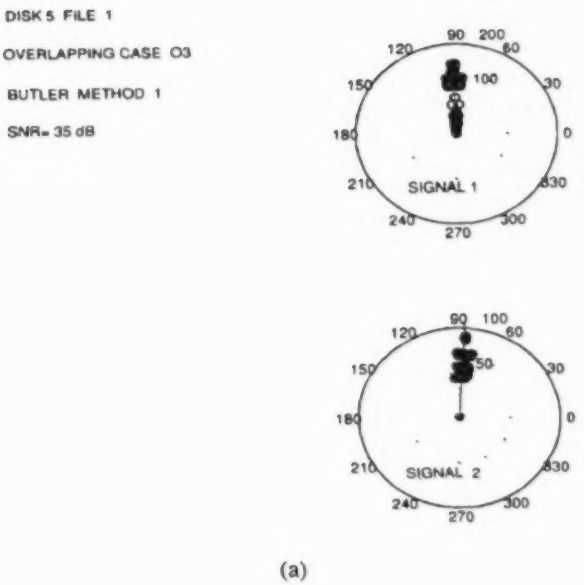

Figure 8: *Compass plots showing the angle-of-arrival for the two frequency hopping signals in disk 5, file 1, with the radius representing the frequencies: (a) SNR=35 (dB); (b) SNR=15 (dB)*

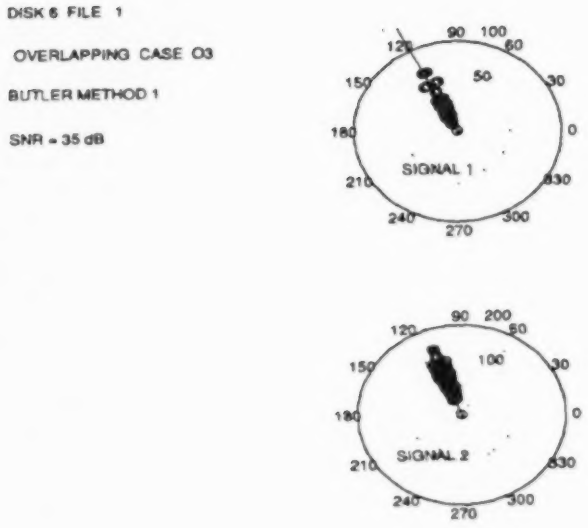

Figure 9: *Compass plots showing the angle-of-arrival for the two frequency hopping signals in disk 6, file 1, with the radius representing the frequencies: (a) SNR=35 (dB); (b) SNR=15 (dB)*

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DIRECTION FINDING PERFORMANCE ANALYSIS FOR DATA COLLECTED DURING THE STORMING BEAI EXERCISE (U)

4. AUTHORS (Last name, first name, middle initial)

KOZMINCHUK, BRIAN, WANG, SICHUN, PATENAUDE, FRANCOIS

5 DATE OF PUBLICATION (month and year of publication of document)	6a NO OF PAGES (total containing information Include Annexes, Appendices, etc)	6b NO OF REFS (total cite document)
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(U) This report presents results for the direction finding (DF) performance obtained using data collected by the Military Digital Analysis System (MiDAS)in November, 1999 during the Storming Bear Army exercise. MiDAS is a software radio based communications EW sensor being developed co-operatively by the Communications Research Center (CRC) and Defence Research Establishment Ottawa (DREO) under the auspices of Defence Research and Development Canada (DRDC) project LIEWA (Land Intelligence Electronic Warfare Automation). The work described in this report addresses approaches for optimizing the DF processing for signals from tactical frequency hopping radios. The DF approach used in MiDAS is based on the Butler matrix approach in combination with a frequency domain implementation of a digital filter bank receiver. Two closely related practical issues concerning the signal processing approach used to generate DF results were addressed. One issue concerns the FFT processing used to obtain the relative phase information used to compute the DF results. The data samples from the Butler antenna array can be divided into non-overlapping or overlapping data blocks, resulting in the non-overlapped FFT or the overlapped FFT. The overlapped FFT is theoretically preferable to the non-overlapped FFT, although at a higher computational cost. The other issue is concerned with the manner in which the angle-of-arrival information from multiple input data blocks is combined or averaged. These issues were investigated in a study where the candidate approaches were implemented and evaluated using raw time domain signal data. The results included the identification of a good approach for combining DF results corresponding to multiple blocks of signal data and confirmation that the Butler matrix approach to DF with overlapped FFT processing is distinctly preferable to the same approach with non-overlapped FFT processing.

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